LA-UR- 04 -0629

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Title: NUCLEAR DETECTION TO PREVENT OR DEFEAT CLADESTINE NUCLEAR ATTACK

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Submitted to: IEEE Sensors Journal

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in transit to U.S. target locations.

- Additional networks of detection systems deployed along U.S. roads and highways to detect illicit nuclear devices that have already entered the U.S. (or were introduced in pieces too small to be detected at our borders).
- Yet more systems deployed at likely U.S. target locations (such as government facilities) to detect illicit nuclear devices before they are positioned for use.

The efficacy of this integrated system must be addressed as a whole; no one layer can be foolproof in all scenarios. Put another way, the question is not whether fielded nuclear detection systems can fully protect the U.S. or not, but how to develop a broader multi-layered system that can do so to our satisfaction. The deployment and enhancement of detection systems is thus one piece of a larger puzzle.

A. *The Role of Detectors*

Nuclear material detection systems have a role in many of the different layers of a defense. Clearly, effective nuclear-material detectors will have direct application in detection systems at foreign ports, U.S. ports, U.S. highways, target locations, etc. Deployed in these locations, they would help to detect the movement of illicit nuclear materials during the many steps that comprise the acquisition, development, and deployment activities of the adversary. Detectors also have a role in the safeguarding of nuclear materials at source sites. They are essential for monitoring the movement of materials within and between facilities that handle SNM and radiological materials.

Effective detection systems also have indirect benefits. For one, they increase the complexity of the planning and preparation necessary to mount a successful nuclear attack. By driving the adversary to more complex and elaborate strategies (by which they hope to foil our detection systems), we increase the probability of detection by non-technical means. For another, effective detection systems provide a measure of deterrence.

Last, but not least, even if they fail to prevent a nuclear attack, nuclear detection systems can reduce negative consequences by forcing the enemy to increase his standoff distance from likely target locations. For example, assume that the enemy perceives detection at ports to be very effective. A small nuclear device detonated in the harbor of a major urban area would produce a smaller effect than detonation in the heart of the downtown area. An analogy illustrates this point: Before the 1998 bombing of the U.S. embassy in Nairobi, clear signs of al Qaeda attack planning against the embassy were evident. We now know that they intended to detonate an explosive device in the embassy garage, which would have caused major structural damage and killed many Americans. Closing access to the garage did not preclude the attack. However, it minimized damage to the embassy building and to U.S. personnel (13 of whom died; most casualties were unfortunate Kenyans in the building next door). Nuclear-material detectors deployed at target locations may detect a threat device in time to stop its use. However, even if they do not, they may force an adversary to attack from greater range, with benefits potentially far surpassing those in Nairobi.

III. Fundamentals of Nuclear- and Radiological-Material Detection

Because of its low intrinsic radiation, detection of SNM presents a much more difficult problem than detection of radiological materials that might be used to construct an radiation dispersal device (RDD). Of the two major types of SNM, plutonium offers reasonable opportunities for passive radiation detection; highly enriched uranium (HEU) presents a more difficult challenge.

A. *Radiation from Nuclear and Radiological Materials*

Table 1 shows that plutonium is a strong source of both neutrons and high-energy gamma rays, which together are difficult to shield. In contrast, HEU is a weak source of neutrons and mainly low-energy gamma rays, both of which can be reduced to very low levels.

Table 1. Radiation from Special Nuclear Material
1 kg of plutonium metal emits (ignoring self absorption):
7×10^7 γ /sec in the 400 keV region
~ 6×10^4 fission neutrons/sec (~1 MeV)
1 kg of HEU emits (ignoring self absorption)
4×10^7 γ/sec at 186 keV (large self absorption due to low energy; remaining flux easily shielded)
5×10^3 γ /sec at 1001 keV (uranium-238)
3 neutrons/sec

1) *Active Interrogation of SNM*

Because of the difficulties with detecting passive HEU emissions, active interrogation with neutrons or gamma rays is currently a subject of renewed interest. Fission produces a small percentage of delayed neutrons that can be observed for many milliseconds after the event. This signature can provide an unambiguous indication of presence of any type of SNM, HEU or otherwise.

2) *Radiological Materials*

One example of an RDD material, cesium-137 from soil-moisture gauges, produces 662 keV gamma rays with typical source strength of tens of milliCuries (mCi; 1 Ci is 3.7×10^{10} disintegrations/sec). The radiation from such a source can be shielded, but a very significant thickness of lead is required to make it undetectable by existing monitoring systems. Soviet-era radioisotope thermoelectric generator heat sources, which contain up to 40,000 Ci of cesium-137 or strontium-90, provide another potential source of RDD material [1]. These sources, while less common and significantly harder to transport than moisture gauges, contain 10 million times the activity [2].

B. *Shielding*

The detection of radioactive materials depends sensitively on their degree of shielding. As indicated in the discussion of SNM, the 186-keV gamma ray from HEU is more easily shielded. Because of its higher-energy photon emissions, shielding plutonium is more difficult.

C. *Natural and anthropogenic background radiation*

Natural backgrounds of gamma rays, neutrons, and charged particles provide a significant limitation to the sensitivity of nuclear radiation-detection systems.

Gamma-ray detector backgrounds occur from cosmic radiation and terrestrial materials that contain uranium, thorium, radium, and potassium. The magnitude of the gamma-radiation background varies with location due to altitude and local material composition. An example of local gamma-ray backgrounds is shown below. This figure shows data from a 3 × 3 in. sodium-iodide detector located on the roof of the Environmental Measurement Laboratory in New York City [3].

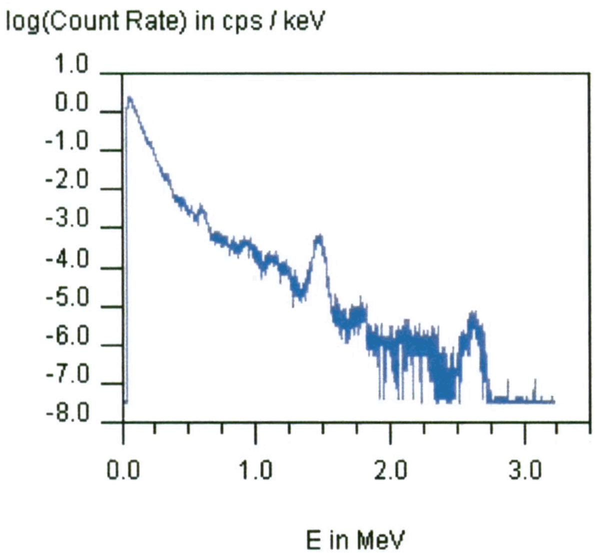

Fig. 1. Gamma-ray spectrum in a 3 × 3 sodium-iodide detector in an urban location [3]. Signals from nuclear material must compete with this structured and variable background.

Neutron backgrounds mostly originate as secondary radiations from cosmic rays interactions in the atmosphere. Neutron backgrounds depend on location (geomagnetic latitude) and altitude, and can vary in time due to solar-induced geomagnetic effects [4]. Background rates of neutrons are lower and less variable than those for gamma rays, but the absence of characteristic energies makes it more difficult to distinguish between source and background contributions

As indicated in Table 2, radiation backgrounds of human origin result from various uses of radioactive material for industrial, medical, and commercial purposes. For example, radioisotopes are used to prevent, diagnose, and treat disease. There are 16 million nuclear medicine imaging and therapeutic procedures performed each year in the U.S. About half of these are cardiac studies using technetium-99m and thallium-201 [5], which involve activities in the few to 10 mCi range.

Table 2. Industrial Sources Commonly Transported on Public Roads [6].
Liquid level gauges
To 5 Ci cobalt-60, others
Radiography sources
50–100 Ci cobalt-60
50–200 Ci iridium-192
4.5 Ci ytterbium-169
Soil moisture density gauges
Americium-241/beryllium neutron sources 200 mCi
Cesium-137, 10s of mCi

Other background sources are ceramics with certain types of glazes, smoke detectors containing americium-241 as an ionization source, depleted uranium used as ballast, potassium-containing fertilizer, and other concentrated masses of potassium, including bananas.

These localized sources can produce false alarms. In a nuclear search, each alarm must be assessed and determined to be harmless. The ability to characterize and reject (in either an automated or manual manner) innocent alarms presents a significant challenge to the design of detection systems.

D. *Basics of radiation detection*

Having described the characteristics of radiation sources and backgrounds, we briefly summarize detection instrumentation. An excellent reference to this topic is Knoll [7]. For all radiations of interest from nuclear or radiological materials, the detection process begins with radiation absorption and ionization energy production in the detection material. The probability of radiation interacting with matter is related to its elemental and isotopic composition. For example, over a wide range of energies, the probability of high-energy photons (gamma- and x-rays) being absorbed (through the photoelectric interaction) varies approximately with the atomic number (Z) to the third power; thus high-Z materials are required to effectively absorb photons. Neutrons transfer energy through elastic scattering, inelastic scattering, and nuclear reactions (with reactions on isotopes such as boron-10, lithium-6, and helium-3 being particularly useful). Low atomic mass materials provide the most effective means of moderating (lowering) neutron energy. Moderation of the neutron energy makes individual neutrons easier to detect, but it reduces the overall flux.

By a variety of primary and secondary interactions, radiation absorption creates electron-ion pairs, electron-hole pairs, or excitations in the sensing medium. The number of ions created in an interaction between radiation and matter depends on the energy of the absorbed radiation, the amount of radiation absorbed, and the physical state of the detector (i.e., gas, liquid, solid).

The efficiency of converting the ion pairs to useful signals is an important property of the detection medium. Detectors function either by converting the ion pairs into light signals (scintillators) or into electrical signals (semiconductors, gas proportional counters, or Geiger-Müller tubes). Overall, radiation detectors must be large (to maximize the chances of capturing each photon or neutron, and to maximize the chance of a single detector absorbing all of the photon energy) and be made of appropriate materials (high-Z for gamma and x-rays; boron-10, lithium-6, helium-3, and hydrogen-1 for neutrons). The trade-offs are price, performance, and availability of materials. For example, many types of scintillators can be made significantly larger than semiconductors, but the direct radiation-to-signal conversion in semiconductors is much more efficient. Inorganic scintillators can be fabricated with high-Z elements, thus providing high gamma-ray efficiencies, but they are significantly more expensive than plastic scintillators. Another important factor is portability. For example, small cadmium-zinc-telluride (CZT) detectors are optimum for a small number of trained inspectors where performance is paramount, while large plastic scintillators are most appropriate for truck monitors where price is critical.

E. *Detection scenarios*

Three categories of detection scenarios need to be considered for detecting nuclear devices, SNM, and illicit radiological materials. The first pertains to controlled detection areas, such as a gate to a military facility or a border checkpoint. The second includes uncontrolled public places already monitored by unmanned radiation monitors, and the third deals with manned searches for radiological materials in areas with no reliable monitoring history. These classes can result in fundamentally different detection strategies.

In the first category, controlled venues, the cargo is under the control of inspectors and a multi-tiered detection approach can be adopted. Here, all techniques are potentially useful, and the best strategy is a staged approach that begins with passive radiation detection and radiography and then proceeds through active interrogation with neutrons and gamma rays. Equipment from simple handheld detectors to sophisticated isotopic identification detection systems may be applicable. False alarms are a major concern, particularly in aggregate, if the inspection process introduces a major delay in cargo processing through a point of entry. Examples of controlled situations are maritime-cargo terminals, official border crossings, air-cargo transfer points, and facility entrance gates.

In the second category, existing unmanned monitors provide a baseline upon which more advanced technologies can be deployed, depending on the nature of the threat. Examples are monitored buffer zones around facilities or interior transportation systems such as public roads, bridges, tunnels, or waterways. In contrast, the third category of unconstrained area search is the most problematic due to the lack of controlled inspection geometry and measurement time and the repercussions of a response to positive, but potentially innocent, radiation detection alarms. Such situations tend to favor the use of larger numbers of less sophisticated, less expensive detectors in order to cover wide areas, with follow-up inspections that involve more capable and expensive advanced technologies.

IV. Opportunities for Progress in Detection Technology

A. *Improving individual detectors*

One way of improving individual detectors is to make them larger, so that they would intercept more of the radiation emitted by the material/weapon. In general, a larger detector will also see more background. Long experience has shown that unpredictable variations in background are the bane of (especially) gamma ray detectors, giving high rates of false alarms.

But backgrounds can be mitigated in various ways, particularly by 1) giving the detectors capabilities to identify the energy of the radiations, so as to distinguish weapon-radiation from background and innocent sources, and/or 2) by giving the detectors a capability to determine the direction from which the radiation is coming, and even to form images of the sources. Two of the detailed case studies of Section V address these possibilities, in the areas of Compton gamma-ray imaging detectors, and large-area detectors derived from neutrino physics research.

B. *Active interrogation*

In active interrogation, engineered sources of neutrons or high-energy photons are used to stimulate enhanced emission of gamma rays or neutrons from plutonium or uranium that might be present in suspect objects such as trucks and cargo containers. It is a known technology in the context of nuclear safeguards, where long interrogation times are acceptable, and comparatively small volumes need to be examined.

Recent advances in ion-source and accelerator technology make feasible factors of 10–1000 increases in the intensity of interrogation sources, with the concomitant promise of being able to scale current prototype package monitors to the size of cargo containers. In addition, smaller, switchable radioactive sources can be deployed in closer proximity to potential SNM targets. These potential improvements are discussed in section V.E.

C. *Radiography*

Radiography with x-ray transmission and backscattering is widely used in transportation for examining the interiors of small- to medium-sized parcels [8,9]. For larger objects, such as truck trailers, radiography using high-energy photons—nuclear gamma rays and bremsstrahlung from electron accelerators—has been developed as a tool to counter conventional smuggling.

Commercially available radiography has serious limitations, however, when searching for comparatively small quantities of SNM imbedded in containers of complex cargo. Qualitatively different technologies hold promise for filling this gap. One such newcomer, for which a small-scale demonstration exists, is radiography using naturally occurring background radiation such as cosmic ray muons. Another approach is fast neutron radiography. However, in the context of searching for SNM or actual devices, fast neutron radiography may be effective in detecting attempts to shield such objects against neutron emission to the exterior, or induced neutron emission (active interrogation). These approaches are discussed in detail in V.C.

D. *Intelligent networks of detectors*

To defend an extended area, one must deploy a large numbers of detectors, probably of heterogeneous types. The false alarm rate can increase to unacceptable levels when many detectors are considered. Results from industrial and academic R&D in large-scale self-organizing networks, wireless communications, and inexpensive and highly accurate GPS and local positioning navigation technologies enable the development of large "self aware" sensor network systems to monitor borders, facility perimeters, or areas for the transport of nuclear or radiological material [10]. Analysis approaches to address this problem include using correlations among networked detectors, in which the logic of the scenario—for example, modeled or observed traffic flow in cities or on highways—is used to reject many sensor false alarms. The network can act as an intelligent system, combining temporal information with data of different kinds to develop a much more comprehensive picture of unfolding events than can be obtained with individual detectors, and thus with manageable false alarms. To obtain a radiation detection network that can cover a large area, the cost of individual sensors must be reduced significantly below current levels.

E. *Detection of non-nuclear physical attributes*

Information from attributes other than nuclear radiation may be of value for preliminary inspections, and any technique which works at ranges greater than those of nuclear radiation would be of great value. Possible screening measurements include thermal, magnetic, mass, and other properties. For long-range detection, attempts are underway to measure atmospheric effects produced by radiation-induced ionization; however, recent analysis conducted at Pacific Northwest National Laboratory [11] indicates that there may not be a sound physical basis for this approach.

V. Case Studies of New Detection Technologies

Considerable ingenuity has been directed at "inventing" new technology to combat the terrorist threat since 9/11. In this section, we discuss a few examples that might convey some of the possible applications of new technologies. The techniques are based on exploiting new sensing channels, rejecting or managing backgrounds, or increasing signal strength, all with the goal of improving sensitivity and/or specificity of threat detection. In each case, we conclude the case study, by asking the impact of the technology on the effectiveness of detection.

A. *Compton imaging of gamma rays*

In the regime of nuclear gamma-ray energy (roughly 0.2–3 MeV), Compton scattering is the dominant photon-matter interaction process. It is impractical to reflect or refract photons to form an image in this domain. Instead, the Compton gamma-ray imager, first proposed 28 years ago [12], reconstructs the direction of individual gamma rays by kinematic analysis of measured energies and directions of scattered particles (Figure 2). This technique is analogous to deducing the direction of an unseen cue ball by observing its deflection and that of the target after they collide. Compton imagers have been built and tested for gamma-ray astronomy [13], medical imaging [14], industrial imaging [15], and radioactive-waste management [16]. As a true imager that segregates source from background, Compton imaging gives a fundamental signal-to-noise advantage over multiplexed imaging systems, such as coded apertures, which modulate signal information within the train of background [17]. Furthermore, Compton imaging naturally provides a wide field of view, typically several steradians. Despite these obvious advantages, the realization of Compton imaging has been a slow process, with past devices limited to large, inefficient astrophysics experiments, and small laboratory test devices in other application areas.

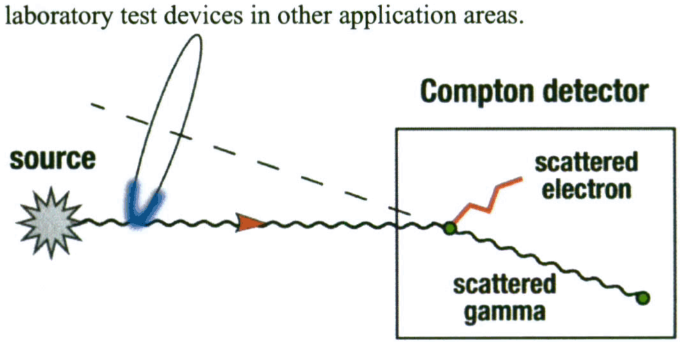

Fig. 2. Compton scattering of a gamma ray, producing a secondary gamma ray and an electron. Kinematic reconstruction of the event can yield the direction of the original gamma ray.

Compton reconstruction of a gamma-ray source can be achieved in two ways. The first technique, annular imaging, is illustrated in Figure 2. In this method, one or more position-sensitive detectors record the location of electron energy loss following Compton scattering. The scattered photon undergoes a second interaction, in the same or a second detector, with this position also being recorded. The detector thus records the energy of the scattered electron and the direction and energy of the scattered gamma. What is lost is the direction of the scattered electron. Without this knowledge, the incoming gamma ray can be reconstructed only to an annulus. All is not lost; by considering the overlap of three or more Compton annuli, the direction of the source can be determined. But the overlapping circles are vulnerable to background confusion. How the overlapping annuli specify a point in space is clearly seen in Figure 3, which shows real data from a recent Argonne-Naval Research Laboratory (NRL) experiment [18].

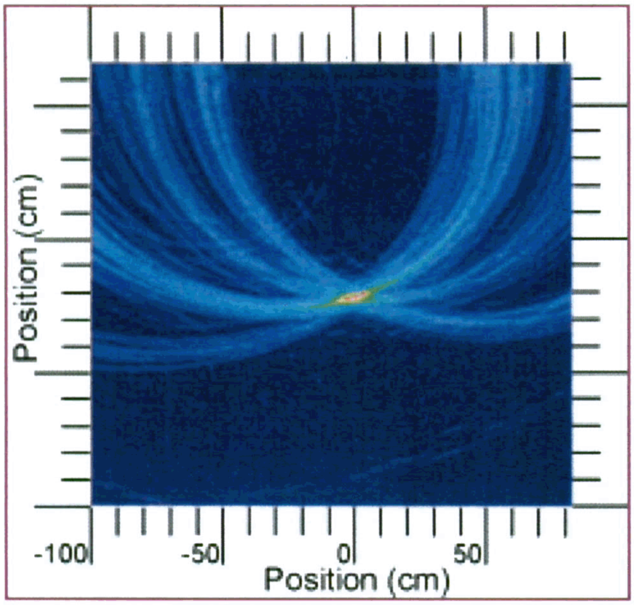

Fig. 3. Intersecting Compton circles from the gamma-ray tracking system pinpoint the location of a radiation source [18].

Technological advances in the past five years make it possible to bring annular Compton tracking technology to the service for national security. Highly segmented germanium detectors with low-noise electronics have been developed by several groups for basic research applications [19]. Sub-cubic-millimeter charge localization can be achieved in detectors with volumes exceeding 100 cm^3. These advances are the building blocks of an annular-imaging Compton spectrometer. As is clear from Figure 3, no technical barriers preclude constructing and fielding such a device today.

The second approach, *full Compton reconstruction,* is more challenging. In the initial Compton scattering, rather than simply localizing the deposition of electron energy loss, an array of ultra-thin position-sensitive detectors is employed to track the electron until it stops, thus defining its trajectory. The Compton-scattered photon is then registered in a second detector that surrounds the electron-tracking array, thus defining its trajectory as well. The direction of the electron must be measured at the very beginning of its trajectory, before its direction changes in an unpredictable way—thus the tracking detectors must be very fine grained. Because multiple scattering is minimized in low-Z materials, silicon is preferred over germanium or other high-Z elements for electron tracking. The combination of electron and photon vectors permits complete reconstruction of the initial scattering, and hence identification of the source location on an event-by-event basis. Signal photons are thereby strongly segregated from backgrounds, making possible the search for clandestine radiation sources at ranges well beyond current practice.

Figure 4 shows schematically how a Compton imager with full reconstruction might be fabricated. The Compton converter material is silicon in the form of 100-micron pitch microstrip detectors oriented alternately in x-y readout planes. The track of the electron is recorded as it loses energy traversing several silicon planes.

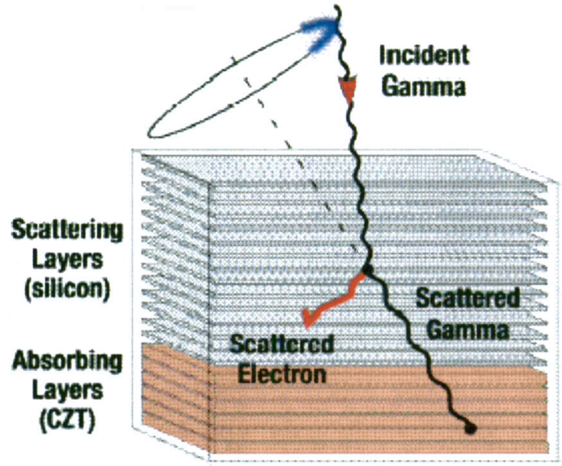

Fig. 4. A schematic representation of a Compton spectrometer with both electron and gamma-ray tracking [20], which can yield full restoration of the original gamma rray.

A total of 200 planes of 100-micron-thick silicon gives 2 cm total thickness of silicon, which assures a reasonable [26%] conversion efficiency. Surrounding this Compton converter is a segmented calorimeter of CZT or other high-resolution material, with sufficient position resolution to localize the second interaction to ~1 mm^3. The silicon strips are read out by application-specific integrated circuits (ASICs) developed recently at Fermilab [21] for collider experiments. The ASICs are bump-bonded to the detector strips—eliminating the need for delicate cables and attendant electronic pick-up problems. Each ASIC is capable of reading out several thousand strips and includes a preamplifier, analogue-to-digital conversion, and a complete digital interface. The total channel count would be 2×10^5 for a 20×10 cm^2 array, very modest by the standard ~10^7 channels of particle physics experiments.

The computing power required to reconstruct events will be significant. To illustrate this problem consider a "standard" event in which a gamma ray undergoes a single Compton conversion in a silicon plane. The electron is tracked through several planes and the Compton scattered gamma ray is absorbed in the calorimeter. But many potentially valid events will occur in which the first Compton gamma ray undergoes a second and perhaps third interaction in the silicon. The intelligence required to recognize the different topographies of valid events is significant. However, much of the required pattern-recognition technology can be imported from other fields where deciphering complex events via increasingly sophisticated levels of "triggers" is commonplace.

Benefit of technology for nuclear detection: Figure 5 shows a simulation of a weak source of 2614-keV gamma rays (10^4/sec). This particular signal, from the rare ^{232}U isotope of uranium, competes with a strong terrestrial background from thorium at exactly the same energy. The simulation assumed that a detector with an effective area of 1000 cm^2 was 25 m from the source, with an exposure time of 1000 sec. The images are, from left to right respectively, from a nonimaging detector, an annular-imaging Compton detector, and a full electron-tracking Compton imager. The source is the green point in the lower left quadrant, visible clearly only in the rightmost image. Of course the nonimager does not produce an image (white panel), just a marginal numeric increase over background. In the images, the clutter away from the true source comes from backgrounds such as terrestrial thorium. Although the source is impossible to detect in 1000 sec at 25 m with the nonimaging detector (it is lost in the statistical variations of the background), it begins to be detectable with the annular-imaging Compton detector, and cannot be missed when observed by the full Compton imager.

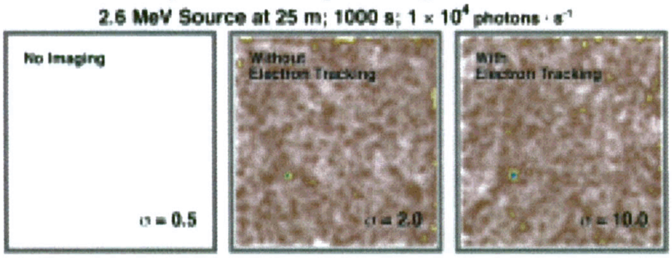

Fig. 5. Signal-to-noise improvement with Compton imaging. A weak source of 2614 keV radiation, undetectable without imaging, is quite significant when viewed by an electron-tracking Compton imager.

In real life, the non-imaging detector fares even more poorly, because it is beleaguered not only by statistical variations in the background, but by systematic but unpredictable variations, for example those caused by variations in the soil composition. An imaging detector is robust against these variations because it can determine the true background by referencing the source pixel to nearby background pixels, measuring the background at the same time it measures the signal. In this case, the full Compton imager would yield a revolutionary improvement in detection capability.

B. *Very large detectors derived from neutrino-detection experiments*

In the following two sections, we examine the application of technology developed in the past ten years for neutrino detectors [22,23], first to the detection of fast neutrons from fission, then to the detection of gamma rays. This application is distinct from the detection of (anti)neutrinos themselves for national security missions [24]. Neutrino, or more accurately, antineutrino detectors are large tanks of liquid scintillator, typically a few hundred tons, in which neutrons, gamma rays, and positrons are detected by registering the combination of scintillation light and Cherenkov radiation in arrays of large photomultipliers[1].

1) Advanced neutron detection

In the post-9/11 rush to deploy radiation detection at transportation portals, comparatively little attention has been paid to neutron detection and the potential advantages to be gained from new technology. Here, we examine the application of "neutrino" detectors to portal monitoring for neutron radiation from illicit traffic in plutonium.

Figure 6 illustrates a typical fast-neutron event in a large-area detector. The neutron enters the active volume and quickly loses energy by elastic scattering on hydrogen. The light produced by the most energetic proton recoils occurs within a few nanoseconds, although the complete neutron moderation to the ambient temperature of the tank followed by capture on hydrogen occurs with a mean time of ~180 μsec.

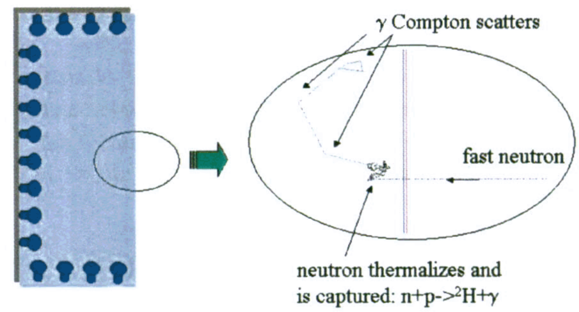

Fig. 6. Schematic neutron detector. A neutron enters the detector volume from the right and quickly loses energy by elastic scattering on hydrogen. The thermalized neutron captures on hydrogen, with a mean time of 180 μsec, producing a 2220-keV gamma ray. The gamma-ray energy is deposited by multiple Compton scattering events.

The coincidence between the two scintillation events (Compton electrons produce both scintillation and Cherenkov light), separated in time by the mean capture time, is a distinct signature of a fast-neutron event.

In order to have a high efficiency for full-energy capture, the "natural" dimension of a large-area detector should be about a meter (making them large-volume detectors as well), or roughly three times the mean free path of the 2220-keV gamma ray in common scintillating materials. Thus, large-area detectors are also highly efficient as stand-alone gamma-ray detectors (discussed below).

The most cost-effective technology for achieving large volume in neutrino detection has been to utilize large tanks of liquid scintillator. Neutrino detectors are usually constructed by immersing the photomultipliers and base electronics in the scintillator itself. This leads to simplicity in construction as well as efficient and robust coupling of the scintillation light to the photomultipliers. When employed as a fast-neutron portal detector, this arrangement leads to the geometry illustrated schematically in Figure 6. The right side of the detector has no photomultipliers, allowing space for the neutron-moderation process. For incident neutrons with energies below 20 MeV, moderation to thermal energies takes

[1] Antineutrino detectors use the reaction $\bar{\nu} + p \rightarrow e^{+} + n$. The neutron is detected when it moderates in the scintillator and is captured on hydrogen producing a 2220 keV gamma ray. Hence, neutrino detectors are naturally both neutron detectors and gamma-ray detectors.

place within 15 cm of the front detector face.

The simple topology of fast neutron events, i.e., moderation of the neutrons within a few centimeters of the front face (without photomultipliers), followed by deposition of the gamma-ray energy some 30+ cm distant, gives a strong discrimination against background events that originate in directions other than the intended field of view of the detector.

Benefit of technology for nuclear detection: In the following example, we consider the advantage to be gained by deploying a large-area fast-neutron detector with 100 times the area of a typical commercial system at a transportation portal. For simplicity we will ignore the difference in detector characteristics, which would likely favor a fast-neutron detector over a standard thermal-neutron detector with external moderation.

Background radiation for cosmic rays and other naturally occurring sources limits the sensitivity of any passive radiation-detection system. We consider the detection of neutrons from plutonium by a typical transportation-portal monitor, and we ask the question, "By what factor is the performance of a monitor improved when its solid angle (area) is increased by a factor of 100?"

Assume that the baseline detection system (a) consists of two 1-m-long, 1-in.-diameter helium-3 proportional tubes. System (b) is a liquid-scintillator detector with solid angle 100 times greater than (a). Employing (a) at a border-crossing portal where vehicles pass at ~8 km/hr, the background count during passage of the vehicle yields 0.06 neutrons, using the known cosmic-ray neutron flux at sea level[2]. But to eliminate false alarms to better than 1 per 1000 passages, Poisson probability dictates that the alarm threshold would have to be set at 3 counts. The background rate for detector (b) is 100 times larger—6 counts—leading to threshold of 15 counts to achieve a comparable rate of false positives. But the gain in sensitivity is

$$\frac{S_b / B_b}{S_a / B_a} = 100\left(\frac{B_a}{B_b}\right) = 20\,.$$

Thus, if detector (a) could sense the passage of 800 grams of unshielded plutonium, the limit for detector (b) would be reduced to 40 g. The gain factors, which depend only on the absolute number of background counts, are in the range 15–30 for typical vehicle-monitoring situations. Because of small-number statistics, the advantage is greater than the $\sqrt{(\mathrm{Area}_b/\mathrm{Area}_a)}$ factor that would apply for Gaussian counting statistics.

Clearly there is an enormous advantage to be gained in setting much lower radiological-material limits at a given false-positive rate. From the viewpoint of false negatives, the small detector is blind to illicit cargoes of plutonium below 800 grams; the large detector functions down to a limit of 40 grams.

2) Large-volume liquid scintillator detectors for large-area search

Sodium-iodide detectors are the general-purpose workhorses for gamma-ray detection in counter-terrorism venues. They have large photopeak efficiencies, modest resolution (~4%), and can be fabricated with reasonably large volumes. Because of their modest size, they are not well suited to search applications with large standoff distances, although cumbersome multi-element systems have been constructed [25].

Large-volume liquid scintillator detectors, developed in the past 10 years for antineutrino detection offer qualitative advantages over sodium-iodide. They can be fabricated with surface areas a factor of 100 or more times that of sodium-iodide "logs," although their photopeak resolution is about a factor of two inferior. The natural dimension of a neutrino detector optimized for gamma-ray detection is about 1 m, set by the 30 cm attenuation length of 1–3 MeV gamma rays in liquid scintillator. Thus a cube, one meter to a side, is about as small as could be manufactured with good photon shower containment. Larger-area detectors retain the one-meter thickness with transverse dimensions defined by the application and by the few-meter limit of self-absorption of scintillation light. Figure 7 shows a possible configuration, possessing directional sensitivity perhaps as good as 30°, using the fast-timing properties of large photomultipliers.

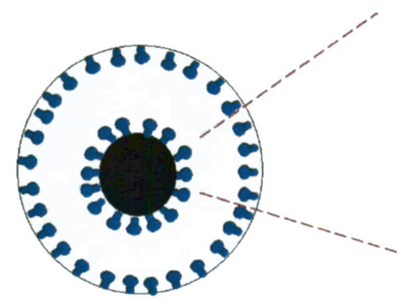

Fig. 7. A possible configuration of a liquid scintillator tank for large-area gamma-ray search application. The dashed lines indicate the approximate directional sensitivity. The blue objects at the perimeters are 8" photomultipliers.

Large-area detectors have high efficiencies for full-energy gamma-ray absorption, which proceeds mainly by multiple Compton events. The energy resolution of a detector is dominated by photon statistics. By using an efficient scintillator, an operating neutrino detector [22] using a pseudocumine-based scintillator has achieved an energy resolution of 7.5%/√E, where E is in MeV. Figure 8 shows the results of simulation of a 1.0 MeV gamma ray in a $2 \times 2 \times 1$ m^3 detector. Note that the 800-keV "Compton edge" is much less prominent than for sodium-iodide detectors, where escape effects are substantial.

[2] Unlike gamma rays, neutron backgrounds are dictated by the cosmic-ray flux, which changes only modestly over short times and distances.

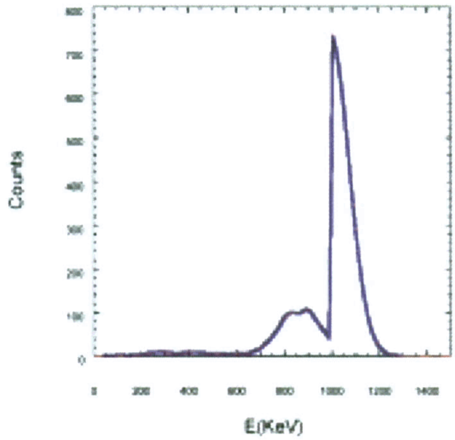

Fig. 8. Simulated gamma-ray energy spectrum for a $1 \times 2 \times 2$ m^3 detector.

Benefit of technology for nuclear detection: Assuming that the signal-to-background rates are comparable in sodium-iodide and in a large-area liquid scintillator detector (escape effects in the sodium-iodide system offsetting the poorer resolution of the liquid scintillator detector), the gain factor from large-area detectors is simple—a factor of 100 in area leads to a factor of ten signal-to-noise improvement, when the noise is dominated by background counting statistics. Based on over a decade of experience by the neutrino-detection community, such detectors are robust, simple to maintain, and may be easily calibrated, monitored, and operated remotely. Detectors using this technology have operated with virtually no component failure for five-plus years.

C. *Advanced radiography*

Conventional radiography to view the interiors of crates, shipping containers, and other objects in transit is currently deployed by the Department of Homeland Security (DHS) in selected locations. Images are formed by penetrating radiation—x-rays, gamma-rays, and bremsstrahlung from electron accelerators. These techniques constitute an effective barrier to smuggling contraband due to their actual and perceived performance. These types of radiography are a mature technology with many commercial vendors in the marketplace [8,9]. Since 9/11, new applications of more penetrating radiography have been considered, for example as a means of detecting SNM hidden in various types of transportation containers. It is clear that not every conceivable smuggling scenario can be mitigated by conventional radiography. This limitation is reason enough to consider new technology.

We consider here two new types of radiography — muon radiography and fast-neutron radiography — in the context of searching for shielded SNM.

1) *Muon radiography*

Muon radiography, in its modern incarnation, uses naturally occurring cosmic rays to tomographically reconstruct dense objects (usually having high-Z) inside large containers—truck trailers, shipping containers, barges in locks, etc. It has the advantage of providing the ingredients of radiography with no artificial radiation, and therefore no dose beyond that naturally experienced. Figure 9 illustrates the concept [26].

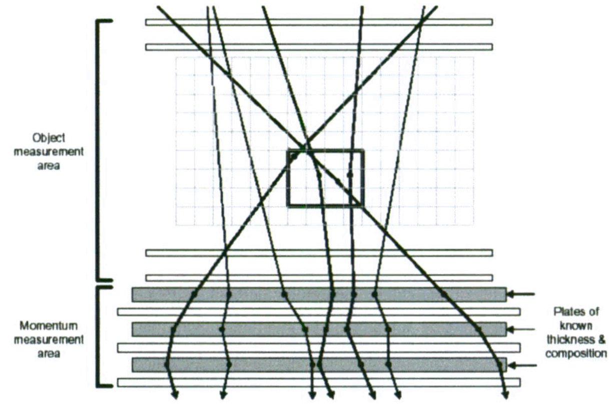

Fig. 9. Cosmic-ray muon radiography concept. In the upper section, scattering of muons is used to identify unknown material. In the lower section, scattering of muons through known material is used to infer muon momentum.

Muons have been used to radiograph dense objects in the past by measuring the fraction of the beam that is absorbed in transit. The most famous instance was the radiograph of the 2^{nd} Pyramid at Giza made by Alvarez *et al.* [27]. However, more information can be gathered in less time if one also takes account of the angular deflection (scattering) of the muons.

Cosmic-ray muons in the GeV range undergo multiple scattering in dense materials, resulting in a small but measurable deflection in their trajectories. Because nuclear material is both dense and high-Z it scatters about two orders of magnitude more strongly than organic materials. Any gamma-ray shielding surrounding a hidden device would simply increase the scattering signal. The measured muon trajectories can be reconstructed to estimate the distribution of strongly scattering objects in a volume. Figure 10 shows simulations of a model problem.

Muon radiography has been taken to the point of a physical proof of principal. Issues that require further investigation include (1) low-cost, large-area detectors, (2) optimum algorithms for object reconstruction, and (3) target signal discrimination in the presence of large clutter in a reasonably short integration time.

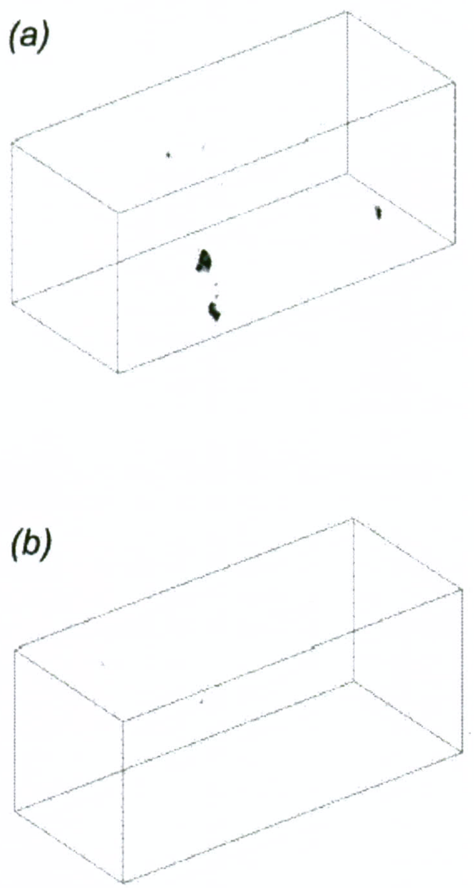

Fig. 10. Reconstructions of one minute of simulated cosmic ray muon radiography of a 6 × 2.4 × 2.4 m^3 cargo container containing 12 tons of iron with 3 buried 9 × 9 × 12 cm^3 uranium bricks (a) and without uranium bricks (b) [28].

Benefit of technology for nuclear detection: It is clear that one does not need to ask anyone's permission to radiograph an object by a naturally occurring background radiation. Muon radiography may be particularly useful when the object has people inside, like a passenger automobile. An important goal would be to detect an assembled nuclear device. Assembled and shielded devices, particularly those made of HEU, are likely to be large and heavy [29]. It is likely that muon radiography could recognize such an object in a short exposure time.

2) *14-MeV neutron radiography*

Energetic photons and muons are sensitive to materials with large atomic number, but they are very insensitive to hydrogen. In contrast, fast neutrons pass relatively freely through lead or iron but are strongly attenuated in hydrogen-containing materials like water and polyethylene. This complementarity suggests the use of fast neutrons to search for shielding that might be hiding a nuclear device in a transportation vehicle. 14-MeV neutrons are particularly attractive because they can be produced simply and cheaply with commercially available sources.

An unshielded plutonium device is a prolific source of fast neutrons, readily detected by even unsophisticated portal monitors. However, a half-meter of borated polyethylene makes it nearly invisible to passive neutron detection. A smuggled device may well be surrounded by such a shield.

The concept is simple: Use photon or muon radiography to locate regions of dense, high-Z material, and fast-neutron radiography to locate regions of substantial neutron shielding (hydrogen-containing substances such as water, oil, plastics, etc). A region of dense material coinciding with a region of substantial neutron shielding should be a rare occurrence in normal cargo. A cubic-meter container of oil with a gamma ray-shielded plutonium device would stand out like the proverbial sore thumb.

Using fast neutrons to search for neutron shielding is fundamentally simpler than photon radiography. First, moderation and containment of fission neutrons requires the equivalent of at least 50 cm of water. Thus the effective size of a neutron-shielded object is at least ~1 m^2: A modest spatial resolution is, therefore, sufficient to characterize a shipping container or other cargo carrier.

Second, unlike photons, 14-MeV neutrons have a substantial probability of passing unscattered through thick objects. Thus rather than scanning the object with a well-collimated beam in order to minimize in-scattering from adjacent pixels, a large-area beam may be used, as depicted in Figure 11.

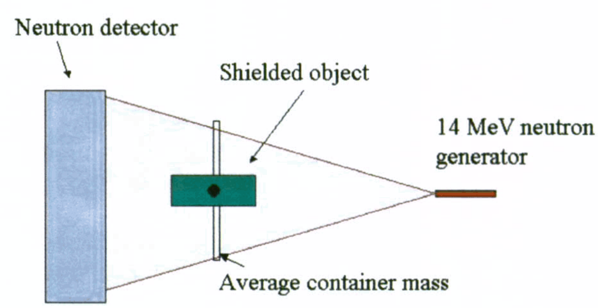

Fig. 11. Schematic radiograph, using a 14-MeV neutron generator to detect neutron shielding.

Figure 12 shows simulated radiographs corresponding to the schematic system of Figure 11. The simulations used a wide-coverage source of neutrons, distributed over an area of 2 × 2 m^2, as could easily be produced by commercially available low-energy D-T generators. The shielded object has a cross sectional area of 0.25 × 0.25 m^3 and a thickness along the neutron beam of 1 m.

Fig. 12. Simulated radiographs of a neutron-shielded object (from left to right) in air, 35 g/cm² of iron, and 70 g/cm² of iron. The left and center radiographs assume 50,000 incident neutrons; the right frame uses 250,000 incident neutrons.

The object is halfway between the neutron source and the detector, giving a magnification of two in the radiographs. The three types of containers are, from left to right, empty (except for the shielded object) and filled uniformly to a total weight of either 10 tons or 20 tons of iron. The right-most frame uses a larger number of incident neutrons in order to compensate for absorption in the 20-ton iron container.

This type of radiography presumes the existence of a large-area fast-neutron detector. This could be a detector of the type described in Section V.B, or thin planes of solid plastic scintillator, with gamma-neutron discrimination provided by time-of-flight from a pulsed D-T generator.

Finally, we note that the radiography described above uses only a small fraction of the intensity available from a typical commercial D-T generator (~10^{9-10} neutrons/sec).

Benefit of technology for nuclear detection: Fast-neutron radiography makes the most sense if combined with a radiographic technique that senses dense, high-Z objects, such as muon radiography or photon radiography. Two radiographs showing a dense object surrounded by substantial neutron shielding would be rare in normal cargo, indicating a very suspicious package.

D. Nonimaging and pseudoimaging techniques for nuclear-material search

The most powerful tool to detect nuclear sources at a large distance is a true imaging detector such as a Compton telescope (see Section V.A). A true imager separates signal from background counts, thereby reducing both statistical and systematic background noise that compete with the signal.

Even without true imaging, there are nonimaging and pseudoimaging techniques that can significantly increase the range and speed of nuclear search. These techniques do not separate signal from background, but they modulate the signal in a known way so that it can be distinguished from background. Although the signal is still mixed with statistical variations in the background, these techniques allow correction for systematic variations in the background—which are often worse than statistical variations. These systematic changes arise from complex variations in the natural- and man-made radiation environment that are difficult to model, but that can yield order-of-magnitude variations in the radiation background [30-32].

As an example, consider the detection of an unshielded, small quantity of uranium-235 in an indoor environment. If one is searching with a 100-cm² detector with sodium-iodide resolution (15% at 186-keV), the detector background will be approximately 10 counts sec^{-1} in the region of the 186-keV line [33]. In 10 seconds, the background signal would be 100 counts, and a real signal, to stand out over the background with 99.5% confidence, would need to be 30 counts. This count rate would correspond to about 1/3 gram of uranium-235 at a distance of 2 m. However, if the background is varying in an unknown fashion, say by a factor of 1.5 times the average, the signal would have to be 2 or 3 times greater than the background to avoid false alarms. In this case the actual detection limit would be a few grams, far worse than the statistical limit. This degradation in performance can be overcome by techniques that measure the background at the same time as the signal.

Nonimaging and pseudoimaging techniques may be available in the nearer term than Compton imaging, and take advantage of large, efficient scintillation detectors that are readily available.

1) Directional sensors.

A nonimaging technique to improve nuclear materials search is shown in Figure 13. Here, a conventional scintillation detector is separated into four segments to provide directionality. Because the incident radiation is attenuated in passing through the detector material, those elements that are facing the source will have a higher count rate. Thus a count-rate asymmetry signals both the nearness of a source and the best direction for further movement. The segmentation measures the local gradient of the radiation field, and it is thereby much less sensitive to position-dependent backgrounds than an omnidirectional detector (sensitive to gamma rays from all directions).

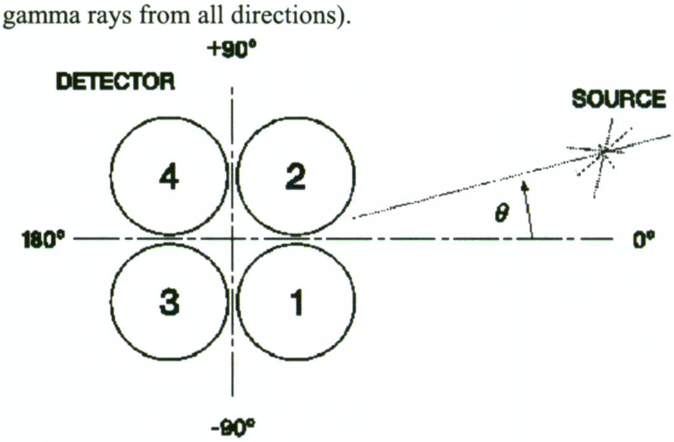

Fig. 13. Geometry of a 4-element directional sensor, designed to facilitate area search.

It has been shown via Monte Carlo simulation and experiment [34] that segmentation greatly decreases search time compared to a single-element detector of the same total volume (Figure 14). In both cases, the assumed detector was a plastic scintillator with realistic energy responses, background, and signal rates. The search was composed of 4-m steps followed by a 60-sec integration time. Success was achieved when the source was located to within 8 m. The conventional-intensity search (labeled Φ) proceeded in the same direction until the summed count rate decreased, whereupon it changed direction by 90° and continued. For a directional search (labeled θ), the step direction was indicated by the detector. Each search was assumed to cover a limited area bounded at 1.5 times the starting separation; if this boundary was reached, the detector was returned to its original location and the search continued.

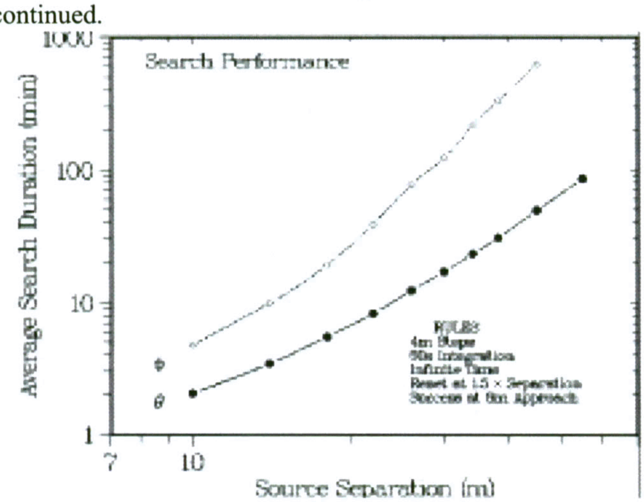

Fig. 14. Time required to find a source for a standard flux monitor (Φ) or a directional detector (θ). The source separation is the initial distance between the searcher and the source.

In this scenario, a source was known to exist, and the search of its assigned area continued until the source was found. The directional detector was twice as fast at the closest source distance, and 10 times faster at 40 m.

2) Pseudoimaging sensors.

A number of techniques modulate the incoming flux to map out the signal (and background) as a function of position. They are termed "pseudoimaging" because they do not segregate the signal from the background and its statistical noise. Rather they map out the background, placing the signal in context. Ziock and Goldstein [35] have shown that the use of pseudoimaging allows one to increase the sensitivity of passive searches for radioactive materials by an order of magnitude or more.

Techniques for pseudoimaging include pinhole cameras, Fourier-transform cameras [36], rotation-modulation cameras [37], coded apertures [17], and scanning collimated detectors. Holt and Priedhorsky [38] showed that all these techniques have approximately the same sensitivity when searching for a faint source in the presence of a diffuse background, as is the case for nuclear search. The detection limit depends only on the level of the background and the detector size. The technique of choice for nuclear search will depend on details such as package size, processing, cost, etc.

Pseudoimaging techniques are based on modulating the gamma rays that reach the detector either in time or in position to encode the image. The coded-aperture imager (Figure 15) is an example of a position-modulated system. In this technique, the incident radiation projects a direction-specific part of the mask pattern onto the detector. The pattern is selected so that the image can be recreated from the data with a mathematically procedure that is similar to cross-correlation.

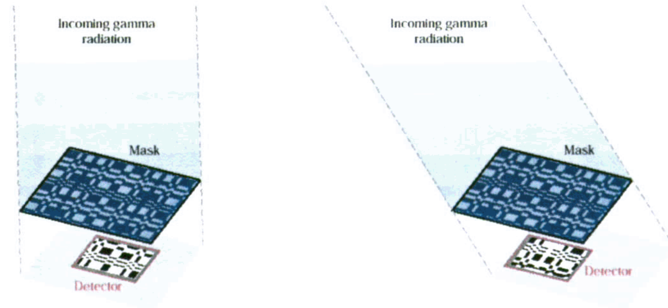

Fig. 15. Schematic view of coded-aperture imaging. Depending on the direction of origin, the incoming radiation projects a unique portion of the shadow mask onto the detector.

Consider the detection of a point source of radiation in the presence of a varying background. Consider a 1 mCi source of cesium-137, in the presence of backgrounds typical for sodium-iodide spectral resolution and an outdoor environment, viewed by a 100 cm^2 omnidirectional detector [35]. The background is perturbed by a linear feature, 45 m long, which doubles the background rate. One attempts to detect the source by driving past it in a straight line at a constant velocity. The range is defined as the distance of closest approach. If the background were constant, the source would be detectable at tens of meters. This is not a realistic situation, because the source is utterly confused by the background variation at distances beyond 10 m. The omnidirectional detector cannot resolve the source signal from background variations, and a larger detector would do no better because the background count would just get larger, not better understood.

One can break through this distance barrier by the use of an advanced imaging technique. Ziock and Goldstein [35] posit a coded aperture imager with 2.8° resolution in the horizontal direction. Figure 16 shows that, with a coded aperture and a 100 cm^2 detector, the source is clearly visible to a range of 20 m. The working range continues to increase with detector size—40 m for 1000 cm^2, and 100 m for 10,000 cm^2.

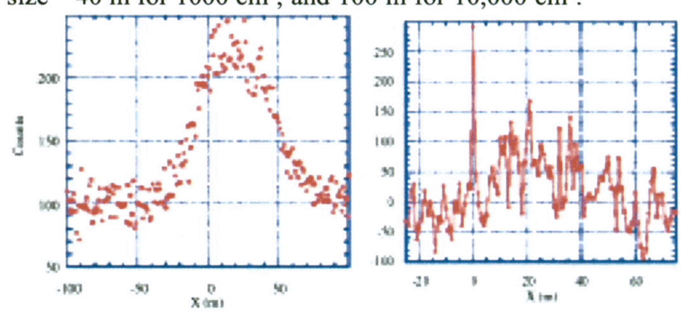

Fig. 16. A pseudoimaging detector can find a source in the presence of a varying background, when an omnidirectional detector is confused. Response of omnidirectional (left) and coded aperture (right) detectors to a 1 mCi ^{137}Ci source at 20 m, in the presence of a 45-m long perturbation of the background by +100%. For the omnidirectional detector, the source disappears into the background perturbation. The coded aperture clearly separates the two [35].

Benefit of technology for nuclear detection: The calculations above demonstrate that directional detectors can decrease search times by up to an order of magnitude, and pseudoimaging detectors can increase detection range in the presence of complex backgrounds by a factor of five or greater, thereby increasing the detection area by an order of magnitude.

E. Active interrogation to detect highly enriched uranium

Because it emits no penetrating radiation, HEU poses a challenge for detection. Its most intense gamma-ray line, at 186 keV, can be attenuated by lead shielding. Only the surface of a large mass of HEU contributes to the output because of self-absorption. A 2614-keV gamma ray produced by the decay of the impurity uranium-232 to thalium-208 also exists, but only when the uranium-232 impurity is present. Active techniques bypass this paucity of passive emissions. A neutron of any energy, or a gamma above about 6 MeV, will cause uranium-235 to fission and emit both gammas and neutrons. Plutonium can be activated in the same way by an interrogating probe. Active interrogation techniques take advantage of the defining characteristic of special nuclear material: its ability to fission.

A major tool against smuggled HEU could be the deployment of active interrogation systems using either high-energy photons or fast neutrons (which can probe significantly deeper into cargoes than thermal neutrons). A recent report by the National Research Council, *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism"* [39], includes the recommendation, "Research and development support should be provided by the Department of Energy and Department of Defense for improving the technological capabilities of special nuclear material detection systems, especially for detecting highly enriched uranium." The report continues, "In the near term, R&D is needed to improve neutron interrogation sources (i.e., neutron generators) and detector systems for HEU."

The feasibility of detecting HEU via active interrogation has been demonstrated in a series of laboratory measurements, which involved a linear accelerator (linac) for interrogation with bremsstrahlung photons [40]. An active interrogation technique employing a D-T neutron generator, the active interrogation package monitor (AIPM), has already been developed to the prototype level [41] (Figure 17). The presence of SNM is indicated by the emission of delayed neutrons that persist after the interrogating pulse. Delayed neutrons are indicative of fission. The AIPM is fully sealed for radiation safety, so neither the interrogating neutrons nor the induced neutrons escape the device.

Fig. 17. The Active Interrogation Package Monitor [41] searches packages and containers for SNM, detecting small quantities of SNM in seconds even in the presence of shielding.

But active interrogation is not yet available on a large scale, for example in devices that could scan a line of containers as they move past. Barriers to acceptance include the size, cost, and power consumption of interrogation sources, the size and cost of detector arrays, and the lack of smart software to fuse the return nuclear signals with other data, such as backscatter radiographs and conventional imagery. Another critical factor is the issue of radiation safety—how can one bombard a target with radiation in an open-air situation without an unacceptable dose to the operators and bystanders?

1) Neutron sources

One approach to improved active interrogation is better neutron sources—smaller, more intense, and longer-lived. Existing neutron sources typically operate by bombarding a solid target with an accelerated beam, yielding neutrons from D-D or D-T fusion. These beam/target sources typically put out $\sim 10^8$ neutrons/sec and have target lifetimes of a few hundred hours. More intense sources would speed the time for interrogation. K.-N. Leung and collaborators [42] have developed a compact neutron generator based on the production of deuterium or tritium ions in a radio-frequency (RF) driven multicusp plasma source, followed by electrostatic acceleration onto a titanium-coated target loaded with deuterium. The neutron generator is the size of a breadbox, with a desk-sized power supply, and is designed to produce 10^{10} neutrons/sec.

Long lifetime can be had by eliminating the solid target entirely, producing neutrons via fusion reactions in a plasma. Direct-current operation of an inertial electrostatic confinement (IEC) source was initially demonstrated by R. L. Hirsch [43] in the 1960s. The neutrons are produced by a spatially converging energetic plasma. Hirsch was able to achieve a maximum neutron yield of 2×10^{10} neutrons/sec for the D-T reaction. Because the IEC system does not require a solid target, it promises to achieve both high output (10^{10} neutrons/sec time-averaged) and long lifetimes (~5000 hrs) in a low-cost source. R. Nebel and colleagues [44] propose to use the IEC approach to produce highly energetic plasmas capable of yielding a peak neutron flux of 4×10^{11} neutrons/sec by D-T fusion with a duty factor of 2.5%. Equivalent D-D yields (there is a factor of 200 conversion between D-D and D-T yields) have been recently reproduced by the University of Wisconsin group operating their IEC at 160 kV and 50 mA [45]. Work is needed to achieve the same time-averaged performance in a pulsed mode suitable for delayed neutron detection, which requires increasing the peak current and peak neutron flux by a factor of 20.

2) Electron accelerator sources

Electron accelerator technology offers an alternate approach fir active interrogation. Particular advantage is to be gained from high-energy gamma rays, readily produced as bremsstrahlung radiation by bombarding a high-Z target with energetic electrons. Bremsstrahlung conversion is efficient; a 10 MeV beam incident on an optimum high-Z target yields about 10% conversion into forward-focused gamma rays (~3° width) with energies above 6 MeV [46]. Higher electron energies produce even narrower beams, but gamma rays above 10 MeV lead to undesirable consequences such as induced radiation and spurious return signals, even from air.

Accelerators that are small, portable, low-cost, and efficient are most desirable. One way to produce such an accelerator is to optimize existing technology, seeking improvements in the performance of every subsystem (power supply, RF source, and accelerator), and exploiting engineered materials for lower weight and power efficiency.

Another path to reduced size and weight is increased frequency, because linear accelerator length scales with frequency. Higher-frequency linacs also promise greater RF power efficiency and higher electric-field limits, which translate into reduced power requirements and greater reliability. There has been substantial work in X-band linacs (11 GHz) in the last ten years because of linear collider development for high-energy physics [47]. Unfortunately, there are no compact high-power microwave sources at that frequency. Carlsten and colleagues propose using new photolithographic fabrication methods to construct a high-power (500-kW traveling-wave tube, or TWT) microwave source in the W-band (95-GHz, or 3-mm wavelength). The key to their approach is an efficient, compact RF source based on a sheet beam traveling wave tube [48].

3) Miniature sources

Another approach to active interrogation is to make the source so small that it can be brought into close proximity with the target, by distributing it in numbers. This takes advantage of the fact that the return signal from active interrogation increases as the inverse fourth power of the distance between the neutron generator and the target. To close in on the target, sources must shrink in size and cost.

Sandia National Laboratory is researching a switchable radioactive neutron source (SRNS) [49]. This new class of miniature neutron generator relies on the reaction of alpha particles (emitted from a radioisotope) with beryllium nuclei to produce neutrons. The SRNS can be switched "on" and "off" remotely by moving the alpha-emitting source in close proximity to a beryllium target (on-state) and reversing the process to stop neutron production (off-state). The ability to turn the neutron generator on and off greatly increases its utility and reduces its size, by making it safe in the off state without heavy shielding.

The SRNS will produce approximately 10^6 neutrons/sec in the on state and will emit safe levels of gamma and neutron radiation in the off state. The size of the device (about the size of a Palm Pilot) is dictated by the amount of the radioisotope (300 mCi of ^{241}Am) needed to produce the required flux of neutrons, and the shielding required to block the residual off-state radiation. A first prototype uses a simple rotational motor to move disks in and out of alignment and thereby turn the device on and off.

These neutron generators will be used in conjunction with neutron and/or gamma detectors to sample an unknown volume for SNM, as depicted in Figure 18.

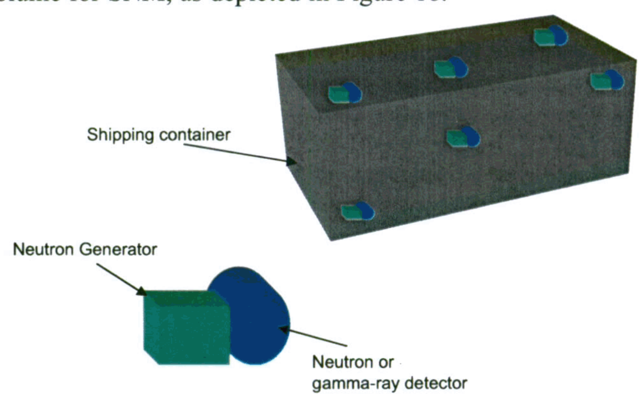

Fig. 18. Diagrammatic representation of one mode of deployment of an array of switchable radioactive neutron sources (SRNS). In this configuration, pairs of neutron generators and radiation detectors are placed on the surface of the item to be interrogated.

Benefit of technology for nuclear detection: As better sources, detectors, and operational schemes are developed for active interrogation, one gains leverage on the hardest problem in nuclear smuggling: the detection of shielded HEU. Without active interrogation, this material is difficult to detect (muon radiography may allow the screening for high-Z material, but not the specific identification of fissionable material). But with active interrogation, one might scan down a line of cargo containers, or a line of stopped (and unmanned) traffic, and within a few minutes confirm or reject the presence of special nuclear material.

VI. Comments on Performance Assessment

Throughout this document, sometimes explicitly and sometimes implicitly, the question of the performance of radiation detection systems arises. How it is quantified at the system level is a significant matter in its own right.

As with other elements of a protection architecture, performance of radiation-based detection systems can be thought of on three levels. At the detailed technical level, metrics for radiation detection can be expressed in terms of detection range, detection time, false alarm rates, type and quantity of nuclear material that can be detected, amount and type of deliberate and incidental shielding around the weapon/material, and other parameters. On an intermediate level, these technical metrics can be interpreted in terms of overall detection systems' abilities to contribute to defeat of attacks in individual scenarios. At the broadest level, performance of the entire prevention/protection architecture would be assessed across the full range of scenarios, including the dynamic interplay between the evolving defense and the attacker's evolving strategies, taking account of the fact that no protection system can be perfect.

These are not trival analyses. At the most detailed, technical level, the utility of detectors in real operations depends strongly on natural radiation backgrounds, which vary greatly from place to place and often in time. Such backgrounds, and the nature of radiation detection in general, introduce a probabilistic element in assessment of performance, and the significance of detection and false-alarm probabilities is very scenario-dependent. All of this fuzzes concreteness, which creates difficulties in assessing system performance and in planning defense.

But it also causes problems for an attacker, and their problems may be worse. If we can raise the performance of detection systems, as we may be able to do, to the level where an attacker must do a similar analysis to be confident of finding the chinks in our defense, we will have reached a significant level of deterrence. For example, for an attacker to have to measure background radiation around a military base exposes him to counter-surveillance that he will fear (or that will catch him).

But no one, including the present authors, has considered comprehensively the dynamic interplay between attack and defense—all of the possible attack modes and defense architectures, as they will interactively evolve. When and if the community involved in this work becomes able to assess system performance against threats accurately and comprehensively, it will be found that the defense is not leak-proof, as no defense can be. Because of this, some might argue that devoting significant resources to new detection technologies would be wasteful. We believe this is profoundly wrong.

VII. Conclusion

Attempts will not be frequent. If, without defenses, there might be a successful attack during, say, the next five years, and if, with defenses, the first successful attack could be delayed for fifteen or twenty years, that would be a successful defense. It could provide time for world changes that could mitigate the underlying political and cultural factors that stimulate this threat (and others). Many of us believe that a strong case can be made that prevention/protection can be developed that will substantially attenuate the frequency of successful attacks.

We need not be defenseless, even in the very near term. Real defenses can be built with today's technology, either off the shelf or assembled from existing components. Much might be done with improved technology that cannot be done today. The boundary between today's reality and tomorrow's possibility depends on the scenario, and the range of scenarios is huge. Still, one can consider some of the improvements that new technology might bring.

Today, only passive detection is readily available. Joint operation of multiple detectors can be done only for a small number of sensors that can be integrated by human intelligence, assisted by limited automatic processing. With these tools,

- Plutonium devices can be detected in vehicles at portals (for example, the gates of military bases), in cargo containers, and in vehicles at speed, if the device is unshielded or lightly shielded.
- Some high-value targets are defensible, thanks to geographic features that channel traffic through defensible chokepoints, where capable portal monitors can be stationed.

These capabilities may be impaired by high and/or variable natural radiation backgrounds, or innocent man-made radiation sources that yield unmanageable false alarm rates.

The technological initiatives discussed in this report would narrow the options available to the attacker, by expanding possibilities for detection. Future benefits include:

- Detection range can be extended by an order of magnitude, opening new defense operational modes, such as rapid, wide area airborne and vehicle sweeps, and monitoring large remote areas and/or extensive road networks.
- Increased range and improved false alarm rejection will enable intelligent networking of detectors. This could enable coverage of road and rail transport over significant distances, for example along the U.S. East Coast, where transport passes through a small number of choke points.
- More portable and longer-lived sources for active interrogation will enable widespread screening of containers and vehicles (whose drivers have stepped away).
- Muon radiography could allow detection of highly enriched uranium in vehicles, whether occupied or not. The greater the shielding, the more effective the detection.

A successful defense can have a strategic impact. No defense is leak proof, but the history of human conflict is rife with real but imperfect defenses that delivered great reduction of risk. Against unconventional nuclear attack, one might build a defense that substantially attenuates the rate of successful attacks, by 1) dissuading many who might consider an attempt, and 2) thwarting a good fraction of the (fewer) attacks that are attempted. New technologies can deliver increasingly more capable defenses.

LIST OF ACRONYMS

AIPM active interrogation package monitor
ASIC application-specific integrated circuit
CZT cadmium-zinc-telluride
D-D deuterium-deuterium
DHS U.S. Department of Homeland Security
D-T deuterium-tritium
HEU highly enriched uranium
IEC inertial electrostatic confinement
Linac linear accelerator
NMR nuclear magnetic resonance
R&D research and development
RDD radiological dispersion device
RF radio-frequency
RFQ radio-frequency quadrupole
SNM special nuclear material
SRNS switchable radioactive neutron source
U.S. United States
Z atomic number

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